

Inclusion of W^\pm single-spin asymmetry data in a polarised PDF determination via Bayesian reweighting

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Summary. — We discuss how the experimental information from longitudinal single-spin asymmetries for W^\pm boson production in polarised proton-proton collisions can be included in a polarised parton determination by Bayesian reweighting of a Monte Carlo set of polarised PDF replicas. We explicitly construct a prior ensemble of polarised parton distributions using available fits to inclusive and semi-inclusive DIS data and we discuss the potential impact of existing and future RHIC measurements on it.

PACS 13.88.+e – 13.85.Ni.

Understanding the spin structure of the nucleon in terms of its parton substructure remains a fundamental challenge in Quantum Chromodynamics (QCD). In this framework, spin-dependent, or polarised, Parton Distribution Functions (PDFs) play a leading role, since their first moments are directly related to quark and gluon contributions to the total nucleon spin (see for example [1] and references therein).

Several next-to-leading order (NLO) QCD analyses based on world data have been carried out in those last years, aiming at an extraction of polarised PDF sets together with an accurate uncertainty estimation [2, 3, 4, 5, 6]. Different pieces of experimental data were included in these studies, thus probing different aspects of the spin-dependent PDFs. Some analyses [2, 3] were solely based on polarised inclusive deep-inelastic lepton-nucleon scattering (DIS), which provides information only on gluon and on the sum of quark and antiquark contributions. Quark-antiquark separation can be achieved by considering other processes, such as charged-current deep-inelastic scattering with neutrino beams (at a neutrino factory), high-energy polarised proton-proton collisions with W^\pm boson production at the Relativistic Heavy Ion Collider (RHIC) and semi-inclusive deep-inelastic lepton-nucleon scattering (SIDIS). Only data coming from SIDIS has been currently included in more recent polarised global analyses [5, 6], but uncertainties on the polarised antiquark PDFs still remain relatively large.

Besides slight differences in the choice of datasets and in the details of the QCD analysis (like treatment of higher twist effects), all these parton extractions are based on fixed functional forms for PDF parametrisation and on the Hessian approach for uncertainty

estimation. This methodology is known to be affected by the intrinsic bias associated to the choice of some parametrisation, and by the limitations of linear error propagation. These issues result in a systematic underestimation of uncertainties, especially in those kinematic regions where the experimental constraints are loose. These drawbacks in the standard approach to PDF determination are more severe for polarised PDFs, due to the quantity and the quality of experimental data, which are respectively less abundant and less accurate than their unpolarised counterparts.

The NNPDF Collaboration has developed an alternative unbiased methodology for unpolarised parton fitting in recent years [7, 8, 9, 10, 11]. Monte Carlo sampling for error propagation and Neural Networks used as unbiased interpolants are the main features of the NNPDF methodology, which provides a faithful statistical representation of PDFs and their uncertainties. The NNPDF Collaboration regularly delivers updated sets of unpolarised PDFs, among which the first PDF set including all available LHC data [12].

Preliminary results on the extraction of a polarised parton set, based on the NNPDF methodology, suggest that some polarised PDF uncertainties might be underestimated in other available PDF determinations [13]. This first NNPDF polarised set is based only on inclusive polarised DIS data, hence it cannot disentangle quark and antiquark PDFs. A possible way to achieve this result could be to include SIDIS data, as in refs. [5, 6]. However, this requires the use of poorly known polarised fragmentation functions, or else their simultaneous determination with the NNPDF methodology.

The production of W^\pm boson in (longitudinally) polarised proton-proton collisions at RHIC will provide independent and clean access to the individual polarised quark and antiquark flavours Δu , $\Delta \bar{u}$, Δd , $\Delta \bar{d}$ [14, 15]. The process is driven by purely weak interaction which couples left-handed quarks with right-handed antiquarks only ($u_L \bar{d}_R \rightarrow W^+$ and $d_L \bar{u}_R \rightarrow W^-$), thus giving rise to a large W parity-violating longitudinal single-spin asymmetry which is sensitive to Δq and $\Delta \bar{q}$ flavour dependence. Production of W bosons occurs at a scale where perturbative QCD is completely reliable and it is free from fragmentation functions since W s are detected through leptonic decays.

The inclusion of RHIC W boson production dataset in the polarised NNPDF parton fit [13] can be performed easily by means of the PDF reweighting technique described in refs. [16, 17]. The method, based on statistical inference and Bayes theorem, consists in assigning to each replica in a PDF ensemble a weight which assesses the probability that this replica agrees with the new data. These weights are computed by evaluating the χ^2 of the new data to the prediction obtained using a given replica. The reweighted ensemble then forms a representation of the probability distribution of PDFs conditional on both the original, or prior, ensemble (including old data) and the new data. It is worth noticing that, after the reweighting procedure, replicas with small weights will become almost irrelevant in ensemble averages, thus being less efficient than their original counterparts at representing the underlying probability distribution.

A major problem in applying the reweighting technique to RHIC data is the fact that W boson production is sensitive to quark-antiquark separation, while the prior polarised PDF ensemble, solely based on DIS data, only contains the sum of quark and antiquark distributions for each flavour. We must therefore construct a prior for the difference of these distributions. This can be done using information on $\Delta \bar{u}$ and $\Delta \bar{d}$ coming from one of the aforementioned fits to SIDIS data, such as DSSV08 fit [6]. If the new datasets bring in a sufficient amount of new information, results will then be almost independent from the choice of the prior [18, 19].

More in detail, we proceed as follows. First of all, we sample the $\Delta \bar{u}$ and $\Delta \bar{d}$ PDFs from DSSV08 [6] at a fixed reference scale $Q_0^2 = 1 \text{ GeV}^2$. We select ten points, half

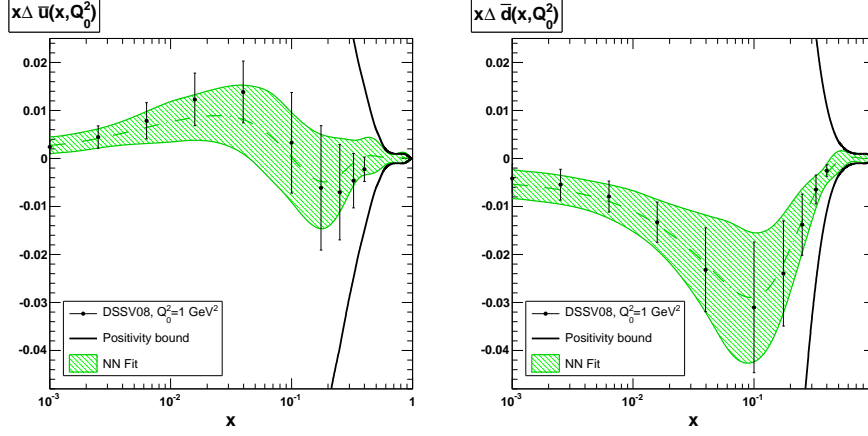


Fig. 1. – The $x\Delta\bar{u}$ (left plot) and the $x\Delta\bar{d}$ (right plot) PDFs from the neural network (NN) fit at the initial parametrization scale $Q_0^2 = 1 \text{ GeV}^2$. Data points sampled from the DSSV08 fit [6] and the positivity bound (see the text) are also shown.

logarithmically spaced and half linearly spaced in the range of momentum fraction $10^{-3} \lesssim x \lesssim 0.4$, which roughly corresponds to the interval of SIDIS experimental data relevant for disentangling quark-antiquark contributions. Then, we generate $N_{\text{rep}} = 100$ replicas of these points with a Gaussian distribution centered at the best fit and with standard deviation given by the DSSV08 PDF error estimate. We check that average and variance computed on the N_{rep} replicas reproduce DSSV08 best fit and error for each sampled point within percent accuracy.

We supplement the input PDF basis in ref. [13] with two linear independent light quark-antiquark combinations, the total valence ΔV and the ΔV_8 , which read, at the initial scale Q_0^2 and with the assumption $\Delta s = \Delta \bar{s}$,

$$\begin{aligned} (1) \quad \Delta V(x, Q_0^2) &= \Delta u^-(x, Q_0^2) + \Delta d^-(x, Q_0^2), \\ (2) \quad \Delta V_8(x, Q_0^2) &= \Delta u^-(x, Q_0^2) - \Delta d^-(x, Q_0^2), \end{aligned}$$

where $\Delta q^- = \Delta q - \Delta \bar{q}$, $q = u, d$. Each of these PDFs is then parametrised by means of a neural network supplemented with a preprocessing polynomial and minimisation is performed using a genetic algorithm as in other NNPDF fits (for details on the general procedure see for example [10]). Positivity constraints are taken into account during the fitting procedure by penalising those replicas which do not fulfill the condition

$$(3) \quad |\Delta f(x, Q_0^2)| \leq f(x, Q_0^2) + \sigma(x, Q_0^2), \quad f = u, \bar{u}, d, \bar{d},$$

where $f(x, Q_0^2)$ and $\sigma(x, Q_0^2)$ are the mean value and the standard deviation computed from the NNPDF2.1 NNLO parton fit [11]. We show the $x\Delta\bar{u}(x, Q_0^2)$ and $x\Delta\bar{d}(x, Q_0^2)$ PDFs resulting from our fit in fig. 1.

We have used this prior polarised PDF ensemble, together with the unpolarised NNPDF2.1 NLO parton set [11], to compute the observables measured by RHIC. To this purpose, we have run the Monte-Carlo code CHE [20], which we have modified to

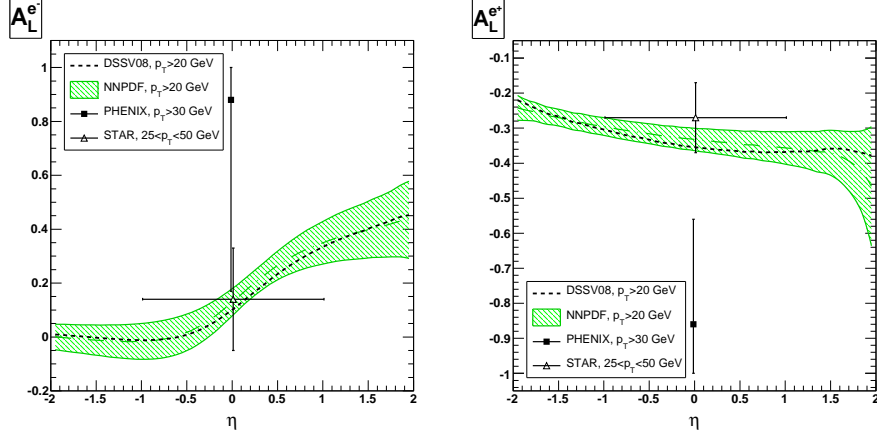


Fig. 2. – Longitudinal single-spin asymmetry A_L^{e-} (A_L^{e+}) for electron (positron) through production and decay of W bosons at RHIC. The dashed curve corresponds to the DSSV08 best fit PDFs, while the dashed-dotted curve and uncertainty band correspond to the mean value and one-sigma error computed within the present NNPDF analysis. We also show experimental measurements (run 2009) from PHENIX [21] and STAR [22] collaborations (uncertainties are statistical only).

allow the usage of NNPDF ensembles. In fig. 2, we show the electron (positron) longitudinal single-spin asymmetry A_L^{e-} (A_L^{e+}) from $W^{-(+)}$ boson production at RHIC computed at NLO using our prior PDF set. The result is shown as a function of the lepton rapidity η , at center-of-mass energy $\sqrt{s} = 500$ GeV². The experimental measurements from PHENIX [21] and STAR [22] collaborations, and the DSSV central prediction are also shown. All theoretical curves are obtained integrating the lepton transverse momentum p_T over all $p_T > 20$ GeV², while the data have $p_T < 30$ GeV (PHENIX) or $25 < p_T < 50$ GeV (STAR). Nevertheless, fig. 2 interestingly sketches the impact of PDF uncertainties on the asymmetry error estimate: at forward (backward) η the uncertainty on $A_L^{e+(-)}$ is large since it is correlated to the large uncertainty found for the \bar{d} (\bar{u}) polarised PDFs. At mid-rapidity, $W^{+(-)}$ production probes a combination of the polarisation of the u and \bar{d} (d and \bar{u}) quarks, and $A_L^{e+(-)}$ is expected to be negative (positive) [20]. Clearly the data from the 2009 RHIC run shown in fig. 2 will have little impact on the PDFs, but those from the 2012 run [23, 24] are likely to have a significant potential in disentangling the individual polarised flavour and antiflavour distributions once included via reweighting.

In summary, we have discussed how experimental data on longitudinal single-spin asymmetries A_L^{e-} and A_L^{e+} from W^\pm boson production at RHIC can be included in a polarised parton fit, based on the NNPDF methodology. We have explicitly constructed a prior PDF ensemble suited for reweighting with these datasets. In future work, we will fully test the impact of RHIC data on our NNPDF polarised parton set through reweighting. By varying the choice of prior PDF ensembles, for example by means of different assumptions on the antiquark distributions, we will then be able to explicitly test for independence of results from the choice of prior, and thus investigate the potential of RHIC data in providing insight into the nucleon spin structure.

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I would like to thank the organisers of QCD-N'12 workshop for the opportunity to present this work and D. de Florian for providing the CHE code. I am also grateful to S. Forte and J. Rojo for useful discussions and for a careful reading of the manuscript.

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